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Quantum Optics Mini-Program on Fast Light, Slow Light, and Metamaterials

Final Report on Santa Barbara Kavli Institute for Theoretical Physics Program (July 8 - July 26, 2002)
Coordinators: R.Y. Chiao, J.H. Eberly, M. Fleischhauer, P.W. Milonni

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A. Goals of the Workshop

The topic of electromagnetic propagation in dielectric media has been enlivened in the past decade by a number of remarkable experimental results showing the technical ability to control the speed of light propagation in exotic ways. Light pulses have been observed travelling faster than c, or slowed by many orders of magnitude, or even stopped completely. All of these results require careful interpretation, and a variety of theoretical interpretations have been proposed and/or published, not all agreeing with each other.

At the same time, in a lower frequency range than optical, rapid development of so-called meta-materials or double-negative materials has occurred. These materials are characterized by electric permittivity and magnetic permeability with very unconventional values, both quantities negative in some cases. Such unusual properties, especially when leading to a negative value for the group velocity, clearly indicate another possibility for control of light. Such materials are being improved rapidly, but independent of their implementation in the laboratory, their theoretical properties have led to dramatic predictions such as the existence of a perfect lens, i.e., a finite lens (actually even planar-flat rather than parabolic) that can deliver an ideally sharp focus unaffected by diffractive effects. There are strong contentions currently being published that such predictions are erroneous.

A principal goal of the Quantum Optics Mini-Program was to collect in workshop format for a few-week period as many as possible of the leading participants in theoretical discussions of these developments. It was hoped to examine the physical reality of the claims and the rigor of the theoretical arguments being published. It was also an open question whether definitions and terminology were being used uniformly. In addition, fundamental questions were open relating to, for example, the influence of quantum noise, the role of measurement, and the significance of intrinsic and extrinsic time scales. In order to provide a connection between theoretical argument and recent laboratory advances it was also a goal of the workshop to include active experimenters among the participants.

B. Specific Projects

1. Double-Negative Materials

In 1968 Veselago (Sov. Phys. Usp. 10, 509) considered media for which both the dielectric permittivity ϵ and the magnetic permeability μ are negative. He showed that such media, while not violating any fundamental physical principles, would have a number of remarkable properties. For instance, light rays would bend the "wrong" way when incident on such a medium, the Doppler effect would be reversed, and the directions of wave propagation and energy propagation would be opposite. Because there are no such naturally occurring materials, Veselago's work was ignored until very recently, when such "metamaterials" (also known as "double-negative" or "left-handed" materials) have been fabricated and studied.

The first week of the mini-workshop brought together some of the leaders in this new and very promising area of research. The lectures by Pendry and Smith both reviewed some of the key concepts in the theory of double-negative media (DNM).

Pendry discussed briefly the limitations to the performance of ordinary lenses. The limit to the focusing resolution, which is the wavelength of the light, is associated with the evanescent field. In the case of a DNM, however, the evanescent field is effectively amplified, and it was predicted by Pendry (Phys. Rev. Lett. 85, 3966 (2000)) that a planar DNM could be a "perfect lens." Pendry described in his lecture how DNMs have been realized. A negative ϵ can be produced with thin-wire structures that behave as a plasma in a microwave field: a negative ϵ follows if the effective plasma frequency is large enough. A negative magnetic permeability μ can be realized, for instance, with split ring resonators etched onto copper circuit board. Pendry showed examples of materials employing both kinds of structures in such a way that ϵ, μ, and therefore the refractive index n are negative. He then went on to discuss various properties of a DNM, including the "super lens" and a "magnetic endoscope."

Smith described the work of the San Diego group that confirms the negative refractive index of the structures they have fabricated. The data from their various experiments are all consistent with the theoretical prediction of negative refractive index, leading to the conclusion that negative refractive index is physically possible and meaningful. Smith went on to report the results of simulations, in particular for the focusing resolution of a DNM lens. His results indicate that a "perfect lens" will be difficult to realize, but that resolution on the order of $\lambda/10$ should be achievable. During discussions he also described simulation and experimental results obtained by his collaborators at Boeing.

There have recently been some strong objections (Phys. Rev. Lett. 88, 187401 (2002) and Phys. Rev. Lett. 88, 207403 (2002)) to the concept of negative refraction and the possibility of "perfect lensing." Both Pendry and Smith addressed these criticisms in response to questions from other participants. Both speakers pointed out that one of these objections (about negative refraction) was based on an erroneous definition of group velocity, while the other (about perfect lensing) had some merit but was much too pessimistic in assessing the possibilities for greatly enhanced focusing capabilities based on DNMs.

Ziolkowski presented results of extensive simulations of DNM structures as well as fabrication and experimental progress. Excellent agreement between simulations and experiment was reported. He introduced a "two-time-derivative Lorentz model" to describe the dispersion characteristics of a DNM, and reported results of simulations in which "superluminal" features of propagation in DNM appeared. There was considerable discussion by him and other participants of the distinction between signal and group velocities and of the definition of the velocity of information transfer. He then went on to describe possible applications of DNMs beyond those discussed previously, including the possibility of extremely high-gain, but extremely narrow-bandwidth, electrically small antennas.

Mojahedi reviewed the notions of signal, information, and energy velocities that have been used historically and in well-known textbooks. There was much fruitful discussion of the interpretation of various recent tunneling and pulse propagation experiments. These discussions continued during the remainder of the first week and into the second week of the workshop.

Eleftheriades reviewed the meaning of negative refractive index and then went on to describe a different implementation of a DNM in which R-L-C elements are periodically loaded in a transmission line. He discussed the point-to-point focusing property that suggests sub-λ focusing in a planar (and *homogeneous*) DNM lens. He then emphasized that, while the 3-D DNM structures made with thin wires and split ring resonators are narrowband and bulky, a 2-D structure can be realized by taking advantage of the transmission line representation of a normal dielectric. In this approach negative ϵ and μ can be synthesized by making the series reactance and shunt susceptance both negative. This results in a large-bandwidth DNM. Results of full-wave simulations were presented. He then discussed experimental results obtained at the University of Toronto in which a "leaky backward antenna," analogous to reversed Cherenkov radiation, was produced and showed excellent agreement with mode patterns obtained with computer simulations. An rf-lens device was also realized with good agreement with simulations. Gaussian pulse propagation in an anomalously dispersive DNM was also discussed briefly. During the discussions Eleftheriades mentioned that sub-λ focusing ($\approx \lambda/20$) had just been obtained by a colleague of his at the University of Toronto.

Chiao posed a question as to the direction of recoil when a wave is incident on a DNM, and a lively discussion continued into the afternoon.

In a talk that had originally been planned for the week devoted to "fast" light, Hagen discussed the recent Bessel beam experiments and argued that the results presented were interpreted incorrectly. In particular, an incorrect group velocity was assumed in interpreting the experiments. During related discussions Chiao raised the issue of the Scharnhorst effect in QED, and Milonni briefly summarized some work by Barton and Scharnhorst and noted that the effect was not necessarily inconsistent with Einstein causality.

2. "Fast Light"

Milonni opened the second week of the workshop with some remarks on Einstein causality. The first question which he addressed is: Why don't the observed instantaneous Einstein-Podolsky-Rosen (EPR) correlations-at-a-distance violate Einstein causality? His answer is that a local experimenter who receives one member of an entangled two-particle EPR pair cannot predetermine the outcome of what she'll measure, although she is of course at liberty to choose arbitrarily the measurement basis (e.g., polarizer setting) she uses to make the measurement. Also, the "no-cloning" theorem guarantees no faster-than-light signaling using the EPR correlations, as an analysis of Herbert's "noise-less amplifier" paradox would show, using the fact that spontaneous emission always spoils the apparent perfect cloning of photons by stimulated emission. Another consequence of no faster-than-light signals is a "no perfect filter" theorem, i.e., there cannot exist a filter that absorbs perfectly at one frequency and affects no others. This follows from a Kramers-Kronig analysis of the complex index of refraction. However, Milonni pointed out a weakness in the standard arguments for no faster-than-light signaling in standard textbooks such as in Landau and Lifshitz, Jackson, etc. The argument is based on the assumption that the refractive index $n(\omega)$ is unity in the high-frequency limit. This holds, of course, in all cases of practical interest. But is there a model-independent (and, in general, a quantum) argument for this limiting procedure which guarantees Einstein causality? Closely related to this question is the fact that causal Green's functions only guarantee that the front velocity travels at the speed $c/\mathrm{Re}[n(\infty)]$. But what guarantees that $\mathrm{Re}[n(\infty)] = 1$? Milonni then reviewed the joint work with Wang et al. (A. Kuzmich, A. Dogariu, L.J. Wang, P.W. Milonni, and R.Y. Chiao, Phys. Rev. Lett. 86, 3925 (2001)), Segev, et al. (B. Segev, P.W. Milonni, J.F. Babb, and R.Y. Chiao, Phys. Rev. A62, 022114 (2000)) that showed that spontaneous emission affects faster-than-light group velocities of laser pulses in amplifying optical media, so as to always limit the superluminal advancement of these pulses, based on a signal-to-noise argument, to values such that the pulse advancement is less than the pulse width. Chiao and Kitano separately pointed out, however, that in amplifying electronic circuits, advancements of voltage pulses which are comparable to the pulse width have been observed in their respective negative group-delay electronics experiments (M. W. Mitchell and R. Y. Chiao, Phys. Lett. A230,133 (1997); Am. J. Phys. 66, 14 (1998); M. Kitano, Am. J. Phys., to be published). Also, in private discussions, Chiao pointed out that Landauer's example of a lighthouse beam sweeping out on a distant wall a spot which moves faster than light, as a model for superluminal motion of wave packets, doesn't work for negative group velocities and negative group delays.

Chiao gave a talk on faster-than-light effects in classical and quantum contexts. Faster-than-c group velocities for smooth, analytic functions, such as Gaussian wave packets, do not violate relativistic causality, but faster-than-c front velocities for discontinuities do. He reviewed the Berkeley experiment (Paul Kwiat's Ph.D. thesis work) demonstrating that faster-than-light EPR correlations occur in the behaviors of two entangled photons at the final beam splitters in two unbalanced Mach-Zehnder interferometers, provided that the two twin photons are observed in coincidence detection (i.e., the "Franson" experiment). One can continuously change correlation-type to anti-correlation-type behaviors in the two photons at the two final beam splitters by continuously adjusting only one arm of the remote interferometer, through which the nearby photon has apparently never passed. The observed visibility of the coincidence fringes violates Bell's inequalities by over 16 standard deviations, thus demonstrating one form of "quantum nonlocality." He then went on to describe the Berkeley experiment (Aephraim Steinberg's Ph.D. thesis) demonstrating that single photons tunnel faster than light, in the sense that the effective group velocity of a single-photon wave packet that contains one and only one photon is transmitted through a tunnel barrier faster than c. This indicates that the process of tunneling in quantum physics is superluminal. Another example of quantum superluminality was the prediction that, due to coherent transmission processes, atoms can pass superluminally through an atomic Bose-Einstein Condensate (BEC) (Chiao, Ropers, Solli, and Hickmann, in Coherence and Quantum Optics VIII, 2001, to be published; see also Proc. SPIE Vol. 4283, p.16-23, Physics and Simulation of Optoelectronic Devices IX (2001), eds. Yasuhiko Arakawa, Peter Blood, Marek Osinski). In a recent e-print, Poulsen and Moelmer (cond-mat/0207029) confirmed this prediction of superluminal atomic transmission, using Bogoliubov-De-Gennes theory applied to the scattering of an atom off an atomic BEC, and predicted that negative group delays for the transmitted atom occur under certain circumstances. The meaning of negative group delay in this example of quantum superluminality is that the transmitted atom leaves the far side of the BEC *before* the incident atom arrives at the near side. Chiao then applied the idea of superluminality to the problem of gravitational wave antennas, and compared a superconductor, which has a macroscopic number of entangled pairs of electrons in the form of Cooper pairs, with a Weber bar as an antenna. The quantum rigidity of the "macroscopic wavefunction" introduced by London is related to the instantaneous EPR correlations-at-a-distance within a single piece of superconductor, and allows a much more efficient coupling to free space of a superconductor to gravitational radiation compared to that of a Weber bar, which has a tiny rigidity. He then went on to describe recent work that suggests that dissipationless, extreme type II superconductors might directly couple microwave electromagnetic to gravitational radiation, and vice versa, in an efficient transducer type of action. The concept of the impedance-matching between these two kinds of radiation inside the superconductor was introduced. Results from a preliminary experiment were presented.

Glasgow introduced the idea of reversibility versus irreversibility in electromagnetic pulse propagation in causal dielectrics. By "reversible vs. irreversible" processes in the dielectric, he meant "available vs. unavailable" energy, upon retrieval of the energy from the dielectric. The dielectric cannot know about the *future* behavior of the pulse, but only the *past*, through the breakup of internal energy into two pieces as follows:

$$u_{int}(t) = \int_{-\infty}^{t} (\mathbf{E} \cdot \dot{\mathbf{P}})(\tau) d\tau|_{available} + \int_{-\infty}^{t} (\mathbf{E} \cdot \dot{\mathbf{P}})(\tau) d\tau|_{unavailable}. \quad (1)$$

He gave two lump-element electronic circuit examples, one of which had two resistors in it, and another with three. The two circuits had identical "macroscopic," i.e., "black box" response functions (or "macroscopic susceptibilities"), but differed in their histories of "microscopic" ohmic heat generated in the individual resistors. Thus a "microscopic" approach would differ from a "macroscopic" approach. He derived an expression for the free energy which depends *only* on the "black box" response function of the entire system, and is *independent* of the particular "microscopic" realization. The surprise of his equivalent circuits was that a naive calculation of free energy (the energy stored in the circuit, i.e., the work done by the drive minus the amount already dissipated by the resistors in the circuit or by the dissipation term in the damped Lorentz model) gave different results for different microscopic models. He used this result to argue against the identification of this naive measure of stored energy with any useful concept of free energy. He instead argued that free energy should be defined with reference to all possible *future* evolutions of the system, i.e., how much energy could be extracted if you chose the *best possible* future drive. This latter quantity proved to be independent of the particular circuit model, and this is what he would call "free energy." It can be derived from the "black box" response function alone, and decreases monotonically in time, after the support of the instigator pulse has passed, and can only be less than any naive instantaneous definition of stored energy (because it recognizes that more energy may be dissipated in any future attempt to extract it). The derivation of this quantity can be written in terms of the instantaneous spectrum, i.e., the spectrum that a drive would have if it followed the real drive up to the present time and were then abruptly truncated. The conclusion is that one must carefully perform an asymptotic analysis based on a concept of the *infimum* of all possible future drive histories of these circuits.

Wang reviewed faster-than-c group velocities of laser pulse propagation in amplifying media. He began with a history of the various velocities introduced by Rayleigh, Hamilton, Voigt, Sommerfeld, Brillouin, Ehrenfest, etc., and the pivotal work of Garrett and McCumber, in which they showed that Gaussian wave packets with narrow bandwidths can propagate with superluminal group velocities with little distortion through an anomalously dispersive medium in the spectral region of an absorption line. He also reviewed Landau's theorem showing that superluminal group velocities are impossible in transparent media. He then reviewed his important experiment demonstrating highly superluminal propagation of laser pulses through an optically pumped cesium vapor cell. A doublet of gain lines in the cell was produced by pumping by a doublet of stimulated Raman pump laser beams. He showed that the peak of an output laser pulse tuned to the transparent spectral region in between the gain doublet left the output face of the cell *before* the peak of the input laser pulse entered the input face (i.e., a "negative group velocity"). He reported the results of an experiment using an electronic circuit to simulate the doublet of gain lines, and showed a pulse break-up effect when one pushes the superluminal effect too far (i.e., a pulse advancement comparable to, or greater than, a pulse width). Wood's anomaly in passive metallic gratings also produced a group velocity of $-c/40$ (Dogariu et al. in J. Appl. Phys., in press). An operational definition of a signal velocity based on the signal-to-noise ratio gives signal velocities less than c. Wang and Lett have answered the question of the sign of the momentum transfer of the cell subjected to transverse Raman pump beams, in which, due to the Abraham force, the cell first recoils *towards* the incident laser pulse, and later recoils *away* from it. (Chiao asked earlier a similar question concerning the sign of the recoil parallel to the surface of an interface between a metamaterial and the vacuum, when negative refraction occurs, during the first week of the workshop on metamaterials). Applications to dispersion-assisted-cryptography were then discussed.

Peatross introduced the concept of the arrival time of a classical electromagnetic pulse defined by means of the "center of gravity" of the pulse, i.e., the Poynting-flux-weighted average of the *time* of a detection by a detector at a fixed position, over all frequencies. This allows a physically meaningful measurement of the time of arrival of broadband pulses. In contrast to "Average energy flow of optical pulses in dispersive media," Phys. Rev. Lett. 84, 2370 (2000) by Peatross, Glasgow, and Ware, which predicted superluminal energy velocities for *narrowband* pulses, for sufficiently *broadband* pulses, no superluminal behavior was found for either absorbers or amplifiers. Glasgow, Ware, and Peatross in their paper "Poynting's theorem and luminal total energy transport in passive dielectric media" (Phys. Rev. E64, 046610 (2001)) have introduced a Poynting-weighted average of the *position* of a pulse, rather than of the *time* of detection, which always leads only to *subluminal* energy transport, in contrast to the *superluminal* energy transport predicted on the basis of the Poynting-weighted average of the time which was predicted earlier in their PRL 84, 2370 (2000). A question arose concerning this point. Eberly pointed out that operationally (and hence physically), detectors detect at a fixed position a pulse integrated over time.

Winful discussed superluminal barrier tunneling in the context of diffusive vs. propagative aspects of the process. After an initial filling time, a static limit is reached for which the tunneling time for opaque barriers is found to be meaningless. Eberly noted the distinction between the Schrödinger equation and the diffusion equation.

Nimtz found an empirical relation for all known tunneling experiments: $\tau \approx 1/f$, where f is the carrier frequency of the tunneling pulse, which is satisfied by all known tunneling time data, including those from the microwave experiments of his group, and also the recent experiments on electron tunneling times by Sekaskii and Letokhov based on field-emission microscopy experiments (Phys. Rev. B64, 2333 (2002)). He argued that band-limited signals (i.e., signals which have compact support in their frequency spectrum) are physical, and not time-limited signals (i.e., signals which have compact support in time), based on the fact that otherwise the Planck relation $E = \hbar\omega$ would lead to unbounded energies. However, he said that Shannon's theory allows signals possessing both finite bandwidths and finite time durations. He believes that information is carried by energy, and not by discontinuities such as fronts. Longhi et al. (Phys. Rev. E65, 046610 (2002)) have sent superluminal pulses with a group velocity of $2c$ in glass fibers in between two regions possessing photonic bandgaps. His group has observed superluminal reflection times, in which no time for the buildup of the reflected pulse was sufficient to explain the observed results. Applications include (1) superluminal mirrors for LEDs and (2) superluminal transmission of digital optical pulses through fibers. Tunneling is a nonlocal process in which one can obtain information on a tunnel barrier's height and width within the tunneling time τ independent of the width of the barrier (in the opaque limit). Eberly pointed out that Nimtz raised a valuable point when he raised the issue of information. Chiao pointed out that in Shannon's theory, information is identified with the concept of entropy, and not with the concept of energy.

Oughstun spoke on the "myth of superluminality in dispersive pulse propagation." He based his arguments on saddle point asymptotics and the notion of the energy velocity, which always turns out to be subluminal, even when the group velocity is superluminal. Precursor analysis show that the pulse breakup effects make the notion of superluminal group velocities effectively meaningless (Xiao and Oughstun, J. Opt. Soc. Am. B 16, 1223 (1999)). The energy velocity was introduced by Barash and Ginzburg (Sov. Phys. Usp. 19, 293 (1976)), and by Loudon JPA 3, 233 (1970), and is always subluminal, making it, and not the group velocity, the physically meaningful propagation velocity. In general, saddle point analysis leads to four contributions: the Sommerfeld precursor, the middle precursor, the Brillouin precursor, and the pole contributions corresponding to the arrival of the signal. Steepest descents must be used for this analysis, and not the method of stationary phase. The middle precursor only appears in double Lorentz lines. See the book by Oughstun and Sherman "EM pulse propagation in causal dielectrics" (Springer 1994), Oughstun, Wyns, and Foty (JOSA A 6,1430 (1989)), and Sherman and Oughstun (JOSA B 12, 229 (1995)). However, Gaussian pulse propagation, which was predicted by Garrett and McCumber, and which was confirmed by Chu and Wong's experiment using picosecond laser pulses propagating inside an absorption line, evades these precursor phenomena by not having any front, but this is only a transitory phenomenon restricted to certain range of propagation distances and moderate opacities, and is not a general phenomenon (Phys. Rev. Lett. 77, 2211 (1996)).

Gauthier spoke on the experiments in his group on superluminal laser pulse propagation as followups of the experiments of Wang et al. He addressed the questions: How far can one push the superluminal pulse advancement ahead in time? What phenomena set in when the pulse advancement becomes comparable to the pulse width? The answer is that various kinds of instabilities set in. His approach was to examine the instabilities associated with bichromatic field propagating in a potassium vapor cell. The choice of potassium, rather than cesium, was based on the fact that the hyperfine splitting was much smaller in the former than in the latter, and was comparable to the Doppler width, which allowed the simultaneous use of the stimulated Raman pumps also as optical pumping beams, and hence the use of a cell with no buffer gas and no paraffin coating. He found superluminal pulse advancement not in the spectral region between the two Raman pump lines, but in the middle region between the lower pump and its lower sideband. There was much pulse distortion in the form of a ringing phenomenon which follows the superluminal pulse peak advancement, when the latter was comparable to the pulse width. Backgrounds due to amplified spontaneous emission (ASE) were also observed. This kind of superluminal pulse propagation effect was not that of Basov et.al.'s "superluminous" propagation effect due to nonlinear saturation of the amplifier by the propagating Gaussian pulse. In single-shot data, a clear "ringing" signal was observed at a frequency equal to the beat note of the two bichromatic Raman pumps. (Chiao suggested that this might be a photon "anti-echo" effect proposed by Jandir Hickmann in his group: The temporal index grating produced by the beating between the overlapping bichromatic pump pulses modulates the light and produces various temporal grating orders, one order corresponding to the usual photon "echo," which follows the two pump pulses, but also another order which corresponds to an unusual, superluminal photon "anti-echo," preceding the arrival of the two bichromatic pulses.) After turning off the probe beam altogether, Gauthier et al. observed a laser-like threshold around 20 milliwatts for a depolarization instability to set in, in which 5 milliwatts of orthogonally polarized light was produced out of noise. This is not a nonlinear Faraday rotation effect. Fantastic spectral broadening due to the bichromatic pumping was observed both in an optical spectrum analyzer, and also in an electronic spectrum analyzer, in which a frequency comb of many orders was observed, which was at least 30 dB above the quantum noise limit. Thus instabilities, rather than ASE, seem to limit the amount of superluminal pulse advancement which could be seen in their experiments.

Recami reviewed his early work on tachyons, which follow from a generalization of special relativity. All superluminal phenomena are called "tachyons." A sign ambiguity in the Lorentz invariance of quadratic forms in relativity, both for space-time and for energy-momentum four vectors, leads to the possible existence of tachyons, provided that one consistently uses the Feynman-Stueckelberg reinterpretation of the particles travelling backwards in time as anti-particles travelling forwards in time. In the case of sound waves, supersonic but localized, X-waves, which are closely related to Bessel beams, have been observed by Lu and Greenleaf (IEEE Ultrasonics 39, 441 (1992)). Electromagnetic Bessel beam solutions analogous to the supersonic X-beams exist, and are superluminal. Recent work by Olkhovsky, Recami, and Salesi (Europhys. Lett. 57, 879 (2002)) showed that tunneling in two successive barriers is superluminal, in that the group delay (or phase time, or Wigner time) for transmission of a particle through both barriers is independent of the separation between the two barriers. Aharonov et al. (Phys. Rev. A65, 052124 (2002)) confirmed using weak-measurement theory that in the case of evanescent waves, the tunneling time in such situations is effectively zero, i.e., that tunneling is effectively instantaneous, independent of the distance traveled by the tunneling particle. Experiments by Longhi et al. ("Measurement of superluminal optical tunneling times in double-barrier photonic band gaps," Phys. Rev. E65, 046610 (2002)) have confirmed these theoretical predictions. Anticipating the work of Peatross, Glasgow, and Ware (Phys. Rev. Lett. 84, 2370 (2000)), Olkhovsky and Recami (1992) defined a probabilistic flux-weighted average time of arrival (i.e., a center-of-gravity in time of detection of particles in a wave packet) for the tunneling time, which led to a prediction of superluminal tunneling. Also, simulations of Maxwell's equation solutions for a waveguide with two beyond-cutoff constrictions showed that *negative* tunneling times are also possible ("Superluminal localized solutions to Maxwell equations propagating along a normal-sized waveguide" PRE 64, 066603 (2001)).

Steinberg reviewed briefly his PhD thesis work which showed that single-photon wavepackets tunnel superluminally, and then went on to discuss in a provisional manner the possibility of the amplification of superluminality. Using the weak-measurement theory of Aharonov to describe superluminal tunneling times, it becomes possible to describe what happens when one embeds an amplifying atom inside the tunnel barrier (e.g., at its midpoint). Simulations show that although the atom does not affect appreciably the transmission probability, it does affect the amount of superluminal pulse advancement of the tunneling wave packet, increasing it substantially beyond the value when the amplifying atom is not present. This is what he meant by "amplification of superluminality (i.e., of the tunneling time)." Steinberg spent most of his time reviewing his recent PRLs dealing with nonlinear optics at the single photon level, in particular the striking phenomenon of a "one-photon switch," in which the presence of one photon can prevent the transmission of another photon in inverse parametric down-conversion. Also, the dispersive aspect of this absorption effect, i.e., the cross-phase shift due to the presence of one photon upon the other photon, was also observed. A theorem about using EIT for quantum information was also introduced for discussion. Chiao in private discussions pointed out an earlier paper by Kurizki and his student Japha in 1997, where an absorbing atom disturbs the tunneling process, so as to destroy the superluminality of the tunneling process by a spontaneous emission event following an absorption event. Steinberg also discussed a claim by Tournois that the reflection time of a Gires-Tournois interferometer operated in a total internal reflection (and hence evanescent-wave) region, was negative. Evidently, Tournois neglected the Goos-Haenschen shift in his calculation, which, when included makes the reflection time subluminal.

Kitano talked on "Group delays in circuits," and gave a live demonstration of a battery-operated electronic circuits, consisting of two boxes in series. The first box consisted of a switch and a four-pole low-pass filter, which emitted a bell-shaped pulse. The second box consisted of an operational amplifier with a simple negative feedback circuit in which a voltage divider consisting of a resistor and capacitor in series to ground delivered a negative feedback signal picked off at the midpoint of the divider. The detectors consisted of two LED lights, which detected the input and the output powers of the operational amplifier. After pushing the button and waiting for the bell-shaped pulse to be produced, the output light lit up *before* the input light lit up. The importance of the "preparation time" between the pushing of the button, and production of the bell-shaped pulse was very large, thus demonstrating the propagation from cause (i.e., the pushing of the button) to the effect (the lighting up of the LEDs) was obviously causal, despite the counterintuitive order of the pulse sequence in which the output LED lit up before the input LED. The complex transfer function analysis of this simple circuit was presented. An optical example of an unbalanced Mach-Zehder interferometer is the optical analog of this electronic circuit. Cascading for larger advancement is restricted by the fact that the effective bandwidth of the cascaded system is reduced, so that the total advancement is proportional only to $\sqrt{n}$, where n is the number of stages, and not to n. Gauthier pointed out that Macke (of Segard and Macke) showed that the bandwidth in a cascaded system decreases as $1/n$, and not as $1/\sqrt{n}$, when distortion of the pulse is taken into account. Hence according to Macke, the total advancement should be independent of n, i.e., there is no increase at all of the superluminal pulse advancement with the number of elements in a cascade, with an increasing number of stages of a superluminal circuit or optical element. Kitano showed that the distortion with increasing the number of elements in an electronic circuit takes the form of ringing or undershooting in the output pulse. Simulations show that although it is possible to push 1 bit with a Rayleigh-resolved superluminal pulse advancement (i.e., by a pulse width), for 5 stages, it requires an unrealistic electronic gain of 10^{15}.

There were many lively discussions which followed these talks in the afternoons. Some of the topics which were discussed were the following: What about the entropy connected with Glasgow's theory? Chiao suggested that in connection with Glasgow's "free energy" concept, there must also be a corresponding "entropy" concept, which follows from the relation $F = U - TS$, where F is Glasgow's free energy, U is the asymptotic internal energy of the "black box" system, T is the equilibrium temperature of the system, and S is then defined as the asymptotic entropy of the system. The heat generated in the "black box" is in general path- or process-dependent, so that infinitesimal changes in heat must be characterized by the path-dependent ("inexact") differential $d'Q$, but the entropy change defined by the "exact" differential $dS = d'Q/T$ should be independent of the path (or process) followed by the system. There was also much discussion on what is meant by "signal" or "information." Should one define a signal in terms of the *global* properties of a signal waveform, such as the energy of the pulse, or in terms of the entropy, as suggested by Shannon's theory? Or should one define a signal in terms of *local* properties, such as the front or some discontinuity in some local derivative of the signal waveform? Is it necessary to distinguish between *virtual* vs. *real* amplification and absorption processes in the case of superluminal pulse propagation in gain media? Is the concept of *virtual* process the same as the concept of *reversible* process introduced in Glasgow's talk? What are the roles of *analyticity* or *nonanalyticity* in the signal waveform? How are Kramers-Kronig relations and relativistic causality precisely related to each other? How does one reconcile these considerations with the Barton-Scharnhorst paradox in boundary-condition modified QED vacua, concerning the faster-than-light propagation inside the Casimir vacuum between two conducting plates?

3. "Slow" Light

The focus of the third week of the mini-program was the controlled manipulation of electromagnetic pulse propagation in coherently prepared media and its application to light-storage, nonlinear optics and quantum information and the connection to aspects of general relativity. The main subjects discussed were fundamentals of slow and stopped light in stationary and moving media, the prospects of transferring the techniques developed for gaseous media to solid state systems, applications of slow light to nonlinear optics and metrology as well as quantum information processing. This week brought together leading experts in these areas from theory as well as experiment.

The week started with a talk by Fleischhauer, who gave a review of the theory of slow light and light storage in stationary and moving media using the quasi-particle picture developed in Phys. Rev. Lett. **84**, 5094 (2000). He addressed questions like what distinguishes light stopping based on EIT from other conventional techniques of optical data storage?, and discussed limitations of light stopping in the absence of explicitly time-dependent interactions. Also the potentials of light stopping for the transfer of flying qubits to stationary qubits and quantum memory were laid out. In this context the important question of the influence of decoherence mechanisms on the fidelity of the quantum memory was discussed. As the storage states are entangled many-particle states the probability of an unwanted environmental interaction to cause a transition to an orthogonal state is very large. Fleischhauer showed that due to the existence of equivalence classes of storage states the enhanced sensitivity to decoherence is exactly compensated, making light-storage a viable candidate for a quantum memory. Finally he discussed some new proposals to use the quantum state transfer between light and atoms to create matter waves in specific nonclassical states (Phys. Rev. Lett. **88**, 070404 (2002)).

In three talks during the week by Scully, Rostovstev and Leonhardt different aspects of slow light and light stopping in moving media were discussed. The question as to what extent moving media can be used for light stopping was put forward and analogies between singularities of wave propagation in moving media and phenomena in black-hole physics drawn.

Scully reviewed the theoretical and experimental work of the group at Texas A & M to slow and freeze light as well as manipulate the properties of stored light in gaseous media with a velocity distribution (Phys. Rev. Lett. **86**, 628 (2001); Phys. Rev. Lett. **88**, 103601 (2002)). He showed that velocity selective excitation schemes together with EIT can be applied to bring light to a halt without transferring all electromagnetic energy to the medium. Making use of atomic motion, different coupling transitions or coupling field modes in the regeneration of a previously stored light pulse, it is possible to spatially transport or time-reverse a stored light pulse or change its carrier frequency. Scully also discussed the potential use of small group velocities of light for resonant nonlinear optical interactions on the few-photon level. He pointed out that, although detailed theoretical descriptions have been developed, no satisfactory physical interpretations of the role of atomic coherences in the different schemes of EIT-based nonlinear optics exist so far. While in the so-called maximum coherence scheme, developed and studied by Harris at Stanford, the strong nonlinear response can be traced back to a maximum ground state coherence, the same is absent e.g. in resonant four-wave mixing schemes.

Rostovtsev gave a short presentation on slow and stopped light in moving media and pointed out the importance and potential advantage of a medium with a spatial dispersion. He then showed that an effective moving medium can be achieved by velocity selective excitation in a Doppler-broadened (hot) gaseous medium.

Leonhardt reported about his recent work to model certain features of black holes associated with wave catastrophies by a laboratory analog using slow-light media. He started off by reviewing some basic features of wave catastrophies as they occur, e.g., at the event horizon of a black hole and discussed the Unruh effect. He then presented a classical Lagrangian theory of slow light in EIT media and predicted for a specific quadratic profile of the control-field intensity the existence of a catastrophic phase singularity near the point of vanishing coupling field intensity, where the group velocity vanishes. (Nature **415**, 406 - 409 (2002)) In a quantized version of the effective theory, the horizon or phase singularity leads to a production of photons reminiscent of Hawking radiation at the event horizon of a black hole. The possibility of such a Hawking-like radiation was then subject to a lively discussion. Fleischhauer suggested that the effective classical theory corresponds to the dark-state polaritons discussed in his talk and suggested that one may have to take into account also the bright-state polaritons which have no singular behavior at the horizon in this system. It was furthermore pointed out in the discussion that the photon production is inconsistent with a microscopic model with quantized electromagnetic fields interacting with three-level atoms. Leonhardt remarked that the approximations made in his approach, in particular the neglect of nonlinear corrections, which may be important close to the phase singularity, will restrict the size of the effect and will lead to an only temporal photon production.

Novel applications of light storage for quantum information processing were the subject of the presentations by Duan and Walsworth, who talked about the theoretical basis and experimental progress towards the implementation of quantum repeaters.

In a lecture that took place during the second week Duan discussed important applications of slow light to quantum communications. He pointed out that many known techniques for long distance communication in classical physics cannot directly be applied to the quantum regime as the no cloning-theorem forbids amplification of arbitrary quantum states. The principal way around these difficulties is given by the concept of quantum repeaters introduced by Briegel and coworkers in 1998. Duan then continued to show that the concepts of light-storage and retrieval using electromagnetically induced transparency can be used to implement the repeater ideas in a potentially very efficient way (Duan et al. Nature **414**, 413 (2001). Finally he discussed a new proposal to make use of the same effects to create in an efficient way entanglement between many atomic ensembles (Duan Phys. Rev. Lett. **88**, 1704 (2002)).

Walsworth gave an update on the ongoing cooperative theoretical and experimental efforts on light storage at Harvard and the Smithsonian Center for Astrophysics with the group of M. Lukin. He presented some recent results in Rb vapor proving the possibility to manipulate the phase of a stored light pulse by magnetic spin rotations during the storage period (Phys. Rev. A **65**, 031802 (2002)). He continued to report on preliminary results towards the implementation of the quantum repeater, discussed earlier by Duan. He presented first data on the measurement of the photon statistics of resonant spontaneous Raman scattering, which is one of the main ingredients of the repeater proposal. The interpretation of these data was discussed extensively after the talk. Walsworth also layed out the future plans of the Harvard team for a better characterization of the light storage process and its limitations in gaseous media and the implementation of a single-photon storage.

An important question for future applications of slow light techniques is whether or not it is possible to transfer them from gaseous media to solid-state systems. Several lectures during the third week focused on different approaches to this goal.

Boyd reported on the first observation of a substantial slowing of light in ruby crystals resonantly driven by a coherent field of moderate strength. When a two-level system is driven by a cw laser field with a Rabi frequency less than the inverse T_2 time, the susceptibility spectrum develops a dip in the absorption right on resonance. Associated with this hole-burning in homogeneously broadened systems is a positive linear dispersion similar to that which occurs in EIT. The dispersion in this system is strong enough to lead to group velocities on the order of 100 m/s. The associated group delay was observed by Boyd and his coworkers. Boyd also mentioned the possibility to see superluminal propagation in solid materials which have two cascaded transitions with almost equal frequencies. Here the absorption profile develops an additional narrow peak rather than a dip, which should lead to group velocities faster than c. He continued to discuss a nanofabricated system consisting of a waveguide evanescently coupled to a periodic array of micrometer-sized ring resonators which sustain whispering gallery modes. This nanofabricated system also leads to a substantial slow-down of light and supports bright as well as dark optical solitons at low intensity levels due to resonator enhanced nonlinearities and dispersion.

Hakuta talked about his work on slow light and nonlinear optics in coherently prepared solid molecular hydrogen. He demonstrated that at temperatures of a few Kelvin almost perfect crystals of parahydrogen molecules can be formed. Electromagnetically induced transparency can be achieved by Raman transitions between the lowest and first excited states of the molecular vibration without excitation of phonons. He demonstrated that in the hydrogen crystal stimulated Raman scattering with self-induced phase-matching is possible due to electromagnetically induced transparency as well as coherent parametric sideband generation ranging from 385 nm to 1206 nm due to maximum coherence (Phys. Rev. Lett. **85**, 2474 (2000)). Hakuta continued to discuss the possibility to observe ultra-slow light propagation in solid hydrogen despite the far-off resonance Raman coupling. He showed that the copropagation and mutual interaction of two sideband modes can be described in terms of two normal modes propagating with nearly c and a strongly reduced group velocity, respectively. Experimental results showed a time delay of 10 ns over a 100 μm crystal length, corresponding to a group velocity of c/30,000 (Phys. Rev. A **65**, 031801(R) (2002)). Finally Hakuta discussed the potential of doped solid hydrogen materials for resonant EIT.

One of the most promising solid-state systems for slow light and light storage are rare-earth doped crystals. Hemmer reported on the work of his group on these systems. He started off with a comparison of light stopping via EIT with other known techniques such as cavity QED, photon echo and Raman excited spin echo and pointed out the advantages of the first. He then argued that the slow-light and light stopping will have the largest potential pay-off when they can be combined with solid-state spectral-hole burning. Ideal candidates for this are rare-earth doped crystals which have GHz inhomogeneous linewidth, long ground-state T_2 times (nsec) and very long ground-state T_1 times (sec). Hole burning by optical pumping and the creation of a narrow anti-hole by back-pumping create the necessary conditions for EIT. Hemmer reported a measured light speed of less than 50 m/s in Pr:YSO, a result which is much lower than the theoretically predicted value and is not yet explained. He showed that it possible to decelerate and accelerate the slow-light pulses and to bring them to a full stop. In contrast to the vapor experiments in the solid-state system with an inhomogeneously broadened spin transition a re-phasing pulse is needed to recover a stored light pulse. His experiments also beautifully demonstrated that under conditions of Raman spin echo a much smaller storage efficiency can be achieved. Finally he discussed several avenues to improve the storage fidelity in rare-earth doped crystals. In particular his suggestion to use a series of well-defined Raman π pulses to lengthen the rather short T_2 time to the long T_1 time, a technique well known from NMR, seemed very promising and was a topic of lively discussed after the talk.

A different type of application of slow light is associated with efficient resonant nonlinear-optical processes and laser metrology. Several speakers had already addressed this issue in their talk, but particular attention was given to this subjects in the lectures by Marangos, Sokolov and Welch.

Marangos reviewed the experimental progress in his group to observe EIT and related nonlinear effects in a MOT system. He reported the observation of transient gain in a four-level double-Λ system, which eventually will be used for experiments on resonantly enhanced four-wave mixing.

Sokolov presented the theory and experimental results on the generation of ultrashort pulses by efficient generation of a large number of Raman sidebands in a molecular system with maximum coherence. Due to the resonant enhancement of the nonlinear coupling coefficient, small density-length products of the molecular vapor can be used for efficient coherent frequency conversion, such that phase-matching considerations are completely irrelevant. With such a technique it is even possible to generate single-cycle optical pulses.

Another very promising application of the large linear dispersion in slow-light materials was discussed by Welch. He reviewed the progress made by several groups using EIT for precision magnetometry. While groups in Berkley (Budker) and Hannover (Wynands) operate in the optically-thin–low-power regime, his group applied EIT techniques in media with large optical density and high laser power. Welch argued that power broadening in EIT media can in principle be exactly compensated by increasing the optical thickness of the medium. In this way it is possible to realize low-shot-noise magnetometers with an extremely large operation regime. He then presented experimental results for an EIT-Faraday magnetometer with a dynamical operation range over 400 mG and a Verde constant of 7×10^3 min/oersted cm. He continued to discuss several specific problems of EIT systems in the high-optical density and high-power regime, such as the influence of ac Stark shifts along with potential methods to avoid them, and the effect of radiation trapping. Finally he discussed ideas for the generation of squeezing using EIT-based nonlinear Faraday rotation.

C. Assessment of the Mini-Workshop

Judging by the enthusiastic discussions and comments by participants, the mini-workshop was very successful indeed. Bringing together some of the leading researchers in the three topics of the mini-workshop produced very lively discussions and new ideas. This was particularly true perhaps of the portion on double-negative materials, where the first report of sub-wavelength focusing was presented and theoretical physicists were able to discuss in detail their different approaches and to learn of the new progress being made by experimental physicists as well as electrical engineers. In the areas of "fast" and "slow" light, similarly, results that have not yet been published or written up were presented, discussed, and in some cases debated. Several people throughout the three weeks remarked at the beginning of their lectures or in private discussions that this was one of the best meetings they had ever attended.

D. Participants and Period of Residence (to be completed by ITP)

E. Manuscripts Completed or in Progress (to be completed by ITP)

F. List of Lectures (to be completed by ITP)